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**BOLT BERANEK AND NEWMAN INC**  
CONSULTING • DEVELOPMENT • RESEARCH

Report No. 2348

*Dr* 1/2

FINAL REPORT

STUDY OF THE FEASIBILITY OF LITHOSPHERIC  
ELECTROMAGNETIC COMMUNICATIONS

16 May 1972

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### Preface

As a task under Contract N00014-72-C-0310 Bolt Beranek and Newman Inc. (BBN) was asked to assist ONR Code 417 in synthesizing an experimental program to investigate the feasibility of achieving hardened communication through the earth over significant ranges using electromagnetic energy if such a communication system is considered to be potentially valuable by the government. This report describes a program plan prepared in close cooperation with ONR Code 417 and based on the state-of-the-art as summarized in American Geophysical Union Monograph 14 and two workshops held in February of 1972 supported by ARPA. BBN is not in a position to know the potential value of such a hardened communication system to the government, and therefore it is not appropriate for this report to be interpreted as a recommendation by BBN.

### Summary and Conclusions

Following a proposal by ONR Code 417, ARPA supported two workshops in February 1972. The objective of the workshops was to investigate the feasibility of developing an experimental program to evaluate whether the electrical properties of the crust or the upper mantle of the earth will allow the propagation of electromagnetic energy through the earth over significant ranges. Bolt Beranek and Newman Inc. (BBN) was asked to attend these workshops, to review AGU Monograph 14 which summarizes the previous work related to this problem sponsored by ONR, and to assist ONR Code 417 in preparing a plan for an experimental program based on the recommendations of the workshops. This report summarizes our understanding of the state of the relevant knowledge concerning the resistivity of the crust and upper mantle of the earth and describes an experimental program to evaluate the possibility of electromagnetic communication through the earth.

The major observations of the report are given below.

A. In spite of considerable speculation and a few limited experiments, there is no reliable data available to either confirm or deny the existence of a zone of resistivity of  $10^7$  ohm-meters or greater required for low attenuation of electromagnetic energy propagating in the crust or upper mantle.

B. It appears possible to conduct an experimental field program to determine whether a zone with resistivity of the order of  $10^7$  ohm-meters exists in the crust using essentially state-of-the-art techniques in a multidisciplinary program. The estimated costs and the major milestone and decision points for a four year experimental program are summarized in Table I. This table assumes the program begins at the start of fiscal year 1973.

Period	July 1972 to February 1973	March 1973 to February 1974	March 1974 to August 1975	September 1975 to February 1976
Objectives	1)choose 2 sites for de- tailed survey 2)perfect field pro- cedures	1)survey 2 sites	1)surveys to extend results to other areas 2)drill and survey an in- termediate depth hole	3)extend 1 site to select a test path
Cost Summary				
Field Surveys	\$ 550,000	\$1,510,000	\$3,940,000	\$800,000
Laboratory and theoretical studies	\$ 330,000	\$ 470,000	\$ 350,000	--
Equipment	\$ 440,000	--	--	--
Drilling	--	--	\$3,000,000	--
Administrative and discretionary	\$ 210,000	\$ 330,000	\$ 500,000	\$ 100,000
TOTAL	<u>\$1,530,000</u>	<u>\$2,310,000</u>	<u>\$7,790,000</u>	<u>\$ 900,000</u>

TABLE I



C. Successful conclusion of these experiments will require a level of coordination among the contributing disciplines, in both field work and interpretation, that is not essential in a more conventional crustal survey. We therefore feel that a strong centralized technical management for this project is absolutely essential if the program is to be successful.

D. Before electromagnetic communication through the earth can be seriously considered to be feasible, not only must the existence of resistivities of the order of  $10^7$  ohm-meters over large geographic areas be demonstrated, but a credible design for a high power transmitting antenna for use in a deep drilled hole must be developed, at least in theory.

E. If electromagnetic communication through the earth is, indeed, feasible, then the cost of such a communication link will be controlled by the need to drill to depths of 5 to 15 kilometers in hard rock to install an antenna. The drilling costs for each land-based transmitting or receiving terminal will probably exceed 10 million dollars and the drilling time will be more than two years with present technology.\*

\*The cover letter for the ONR proposal for this program points out that this cost would not be out of line with that for other hardened communication systems.

## I. BACKGROUND

Following a proposal by ONR Code 417, ARPA supported two workshops in February 1972 to investigate the feasibility of developing an experimental program to evaluate scientifically the question of whether or not the electrical properties of the crust or the shallow upper mantle of the earth will allow the propagation of electromagnetic energy through the earth over significant ranges. Previous work done by ONR to evaluate the present state of our knowledge is summarized in American Geophysical Union Monograph #14<sup>1</sup>.

Professor George Keller of the Department of Geophysics of the Colorado School of Mines was chairman of the "Electromagnetic Crustal Studies Workshop" held 10-12 February at the Colorado School of Mines. Professor Anton Hales, Director of the Geosciences Division of the University of Texas, Dallas, was chairman of the "Multidisciplinary Crustal Studies Workshop" held 14-16 February, also at the School of Mines. The electromagnetic workshop recommendations<sup>2</sup> were prepared by Professor Keller from contributions of the members of the electromagnetic workshop, and the multidisciplinary workshop recommendations<sup>3</sup> were prepared by Professor Hales from contributions written by participants in that workshop. A list of participants is included in each of the workshop reports.

Over the past ten years there has been considerable speculation, and a few limited experiments, exploring the feasibility of establishing an electromagnetic communication path through the earth, all with negative results. In spite of this discouraging record, the conclusions of the workshops held to explore this problem were that 1) valid technical explanations exist for each

failure, and 2) no previous results preclude the existence of a suitable high resistivity layer in the deep crust capable of being used for communications by electromagnetic waves. New understanding based on mineralogical deductions from field observations, understanding of crustal resistivity measuring techniques, and the recently observed interrelationship between seismic and electrical properties of earth materials have led the workshop participants to take a position of "guarded optimism" over the possibility of finding rocks with resistivities on the order of  $10^7$  ohm-meters in the earth's crust. They feel that we are now in a reasonably good position to be able to identify crustal sections in which the resistivity is likely to be greater than  $10^6$  ohm-meters, provided that the sites are carefully chosen. There is also reason to expect that seismic characteristics of the resistive sections may enable us to extend these measurements into regions where precision in the electrical measuring technique is badly degraded by high surface conductivities.

Under Contract N00014-72-C-0310, two members of the technical staff of Bolt Beranek and Newman Inc. attended the workshops as observers and have been providing technical assistance to ONR Code 417 in the preparation of a plan for an experimental program to investigate the feasibility of using the solid earth as a communication medium for electromagnetic waves. This report presents a suggested program with estimated costs and critical milestone/decision points based on data from the workshop reports, AGU Monograph #14<sup>1</sup>, and discussions with workshop participants.

## II. TECHNICAL CONSIDERATIONS

If a zone of high resistivity ( $10^7$  ohm-meters) exists in the crust or upper mantle, both laboratory and field observations suggest that the upper boundary will be controlled by the presence of free water (but generally not by hydrated water in the crystal structure). Laboratory measurements seem to suggest that, in stable geologic environments where the crust is cooling, any water present will be included in the crystal structure as water of hydration so that the rock will essentially be dry and, therefore, probably highly resistive electrically. Seismic characteristics of the lower crust and upper mantle (Poisson's ratio and attenuation) tend to support this conjecture.

It is generally accepted that the lower boundary of a high resistivity zone will be controlled by temperature, but definitive laboratory measurements (accounting for both pressure and temperature on resistivity) required to estimate the depth and form of this boundary have not been made on an appropriate series of rock materials.

Electrical properties at selected test sites will be the primary geophysical data sought by the surveys. However, due to ambiguities in the interpretation of electrical data when the number of significant layers, the transition zones between them, and the lateral inhomogeneities are unknown, electrical measurements alone are expected to be able to confirm or deny the existence of resistivities of only  $10^6$  ohm-meters or slightly greater under favorable surface conditions. Seismic and heat flow measurements supported by appropriate laboratory studies are expected to constrain the inversion of the electrical measurements to allow resolution of resistivities of  $10^7$  ohm-meters or greater. As

indicated in reference 3, p. 2, a zone with resistivity of  $10^7$  ohm-meters should allow electromagnetic transmission ranges of several thousand kilometers.

The sites chosen for the detailed surveys will be selected on the basis of the need for a highly resistive ( $10^4$  ohm-meter) laterally homogeneous surface layer to insure successful electrical field measurements using state-of-the-art techniques in a region where we would expect to find a highly resistive deep crustal section (shield areas are currently thought to be prime places to look). If these likely prospects yield the highly resistive crustal sections sought, we will then extend the study outward both to characterize the likelihood of finding the resistive section in other geologic provinces and to establish a good initial test range for an actual propagation test. Extrapolation of these surveys to estimate the lateral extent of the high resistivity channel will be based primarily on seismic measurements which are less affected by near surface conductivities or inhomogeneities.

The suggested experimental program includes the drilling and surveying of an intermediate depth hole (3-5 kilometers) to confirm the geophysical results inferred from surface measurements before initiating a costly prototype experiment to perform actual propagation tests.

If a communication channel exists, it will be on the order of 5 to 15 kilometers deep and overlain by a highly conductive water-saturated layer. As a result, two crucial engineering problems which have already plagued experimental efforts\* must be

\*In conjunction with this project plan, ONR Code 417 is preparing a brief review of a previous experiment in which the antenna inefficiency appears to have been the major cause of failure of the experiment.



solved. These are: 1) adequate techniques for drilling and suitably insulating very deep holes in crystalline rock, and 2) antenna designs for use in deep holes capable of inducing the necessary high current moment in the deep strata with minimum leakage into the borehole fluids and the overlying conductive layer.

### III. SUGGESTED EXPERIMENTAL PROGRAM

#### A. Introduction

The experimental program outlined here will take approximately four years if results are positive at each major milestone. The total cost for the four year program is estimated to be about 12.8 million dollars. The next step in the development of a hardened through-the-earth electromagnetic communication system after the end of this program would be to begin drilling the necessary deep holes (5 to 15 kilometers) for the terminal antennas of a prototype propagation/communication experiment.

The suggested program and cost estimates are based on recommendations and costs presented in the workshop reports<sup>2,3</sup>. The program recommended by the workshops has been modified in two ways:

- 1) the program has been detailed (e.g., specific numbers of sites) and the part of the program considered in detail has been extended through to selection of a test range, and

- 2) the schedule has been phased to achieve modest reduction in the funds committed in the early stages before positive results at some survey site are obtained. We believe this ordering of the field effort also makes better use of existing facilities and may save purchase of new equipment or use of commercial field crews (neither of these costs is included in the workshop estimates) for parallel field effort at the two primary sites and at sites representing other geological conditions.

The suggested program schedule is, to a great extent, controlled by field seasons and the time required for ensuing data interpretation. The measurements in each field season, particularly in the first two phases, are concentrated on acquiring data needed for the succeeding milestone/decision point.

Three major decision points (and, therefore, four phases of effort) are identified in the program outlined below. In discussing the program we will first briefly describe the objectives, primary activities, and cost estimates for each of the four phases and then describe the objectives of the support activities that go on at roughly a constant level throughout the program.

Since these major phases of the program are geared to field seasons, they do not correspond to fiscal years. We therefore relate the cost estimate to fiscal years at the end of the program description.

Finally, in order to allow some flexibility for satisfying budgetary limitations and/or pressure for early results, we consider possible alternate schedules to accelerate or slow down the program.

## B. The Experimental Program

### *First Phase Program: Site Selection and Technique Development*

The first phase program will have two major objectives:  
1) to select two sites (at the discretion of the Program Manager) suitable for detailed surveys and 2) to develop the field techniques necessary for the surveys.

The early phases of the site selection are discussed in Section I.F. of reference 3. It is expected that the selection team will visit on the order of 5 sites and that 2 or 3 sites will be selected for reconnaissance surveys toward the end of the first field season. The reconnaissance surveys will consist primarily of spot electrical measurements made with the available equipment proposed for use in the detailed surveys during the second year

(see reference 2). In addition short seismic refraction (about 15 km) lines (see reference 3, section V.B.2.) and aerial electromagnetic surveys (reference 2) will be made. Use of electric measurement equipment and techniques proposed for the later detailed surveys will allow checkout of the equipment simultaneously with and contributing to the reconnaissance surveys.

Since shear wave velocity is expected to be crucial in estimating water content during the second year, investigation of potential controlled shear wave sources will be conducted during the first year (reference 3, section V.B.5.). This investigation may lead to initiating procurement or development of a shear wave source for use during the second season.

The project manager will have some discretionary funds for use in additional measurements (e.g., passive seismic observations) on a site-by-site basis as such measurements appear justified.

The total cost of the first phase program including theoretical and laboratory measurements discussed later appears to be about \$1.5M, distributed as follows:

a) Site selection team	\$ 40K
b) Field measurements	400K
c) Seismic equipment and Vibroseis tests	440K
d) Laboratory and theoretical studies	330K
e) Management, interpretation, and discretionary funds	170K
f) Oceanic experiments and equipment to take advantage of ships of opportunity (see discussion of third phase)	150K
Total	<hr/> \$1,530K

The first milestone, selection of two sites for detailed survey during the second phase, is expected to be reached about mid-February of 1973 so that final planning of the second phase program and a final budget for the second phase can be ready by the end of March. If suitable sites for use of existing survey techniques cannot be found, major revision or cancellation of the rest of the program may have to be considered at this time.

*Second Phase Program: Detailed Survey of Two Sites*

The objective of the second phase of the program will be to determine the resistivity vs. depth profile for two selected sites to a precision that will recognize resistivities of  $10^7$  ohm-meters or greater in the crust. The field program at each selected site will include the electrical measurements described in reference 2, four interlocking long line (150 km) seismic surveys as described in reference 3, and the heat flow measurements as described in reference 3. Other measurements (e.g., gravity, magnetics, etc.) will be made as appropriate at the discretion of the project manager. If possible, the seismic measurements will be made using controlled sources for both compression and shear wave energy.

The total cost for this second phase program is expected to be about \$2.3M. This cost estimate assumes that both sites are reasonably accessible. If it were necessary to go to an area such as the Barren Lands of northern Canada to find appropriate field site conditions for the electrical measurements, then the cost for the second year program would be at least doubled. This possibility will be resolved at the time of site selection in February of 1973, and appropriate modifications to the program may have to be made at that time.



The costs in this phase of the program will be distributed approximately as follows:

a) Field program (electric, seismic, heat flow, gravity, and magnetic)	\$1,510K
b) Laboratory and theoretical studies	470K
c) Management, interpretation, and discretionary funds	<u>330K</u>
Total	\$2,310K

At the conclusion of the interpretation of the second year field data, the likelihood of the existence of a zone with resistivities higher than  $10^7$  ohm-meters in the earth's crust should be known. This is the most significant milestone/decision point in the program. If the required resistivity is shown to exist at one or both of the test sites, then it is likely that electromagnetic communication through the earth can be realized in some regions. If, on the other hand, it is found that resistivity could not reach  $10^6$  to  $10^7$  ohm-meters at either test site, there is virtually no chance that long range propagation of electromagnetic waves in the earth can occur; and the project should probably be discontinued. The interpretation should be finished in February of 1974 so that plans for the continued program can be made during March.

*Third Phase Program: Extrapolation to Other Regions and Start of Test Hole*

Once the existence of a high resistivity zone is reasonably certain, the pace of the project can confidently be accelerated. The two objectives of the third phase of the program will be 1) to extend the results of the surveys at the two selected sites in order to estimate the regions in the world where the crustal electromagnetic waveguide is likely to exist

and 2) to drill and survey an intermediate depth hole at one of the two selected sites to confirm the results of Phase 2.

Since surface conditions required for measurement of a deep high resistivity zone by electrical survey methods are unlikely to be found in many geologic areas outside of the selected test sites, the extension of the waveguide characteristics to other geologic provinces will have to be based on measurements less sensitive to surface conditions. Seismic techniques are most likely to give the necessary detailed data, but petrological studies and other geophysical measurements will make valuable contributions to the interpretation. In this phase we assume surveys in 3 to 5 sites in varying geological provinces, designed to estimate 1) the depth of occurrence of water filled pores, 2) the temperature and heat flow in the crust and upper mantle, and 3) the most probable rock types to be found at depth (i.e., to estimate deep resistivities by indirect geophysical means).

The measurements required for determining the existence of the waveguide in suboceanic parts of the crust are logically included in the third phase program\*. However, since a major part of the cost of an oceanic program is likely to be ship time, we recommend that approximately \$150K be available from the beginning of the program to make use of ships that may be available for some of the oceanic measurements (see Phase 1 cost estimates, page 11). The cost of the oceanic experiments can be cut by as much as 50% if some of these experiments can be added to already planned voyages. The cost for the third year program assumes available

\*This subject will be discussed in the ONR cover letter concerning the overall project.

voyages of opportunity are found for part of the oceanic program during the first two phases of the project. If no such opportunities occur before the third phase, we suggest that arrangements for ship time be made to complete the oceanic part of the project during the third phase.

Because of the extremely high cost of drilling deep holes for the final propagation tests and communication demonstration, we suggest that an intermediate depth hole (3 to 5 km) be drilled at one of the survey sites. Using this hole the results of phase 2 of the program can be confirmed (reference 3, section I.C.) and refined. When selecting a site for this hole, attention should be given to the possibility of deepening it and using it for one of the terminals for the prototype propagation and communication experiments.

The third phase cost estimates are summarized below:

a) Field survey in other geological areas	\$3,200K
b) Oceanic surveys (if ELF experiment not completed earlier, add 300K ship time)	300K
c) Drilling cost	3,000K
d) Survey intermediate depth hole and existing pilot hole	440K
e) Laboratory and theoretical studies	350K
f) Management, interpretation (including compilation of existing data, interpretation, and discretionary funds)	500K
• Total	\$7,790K

*Fourth Phase Program: Selection of a Test Range*

The objective of the fourth year of the program will be to select a path for prototype experiments in propagation and communication using the crustal waveguide.

If the results of this four year program are positive and continuation of the project is appropriate, the next step would be to implement an experimental communication link using the crustal channel. It would be most efficient to be able to deepen the intermediate depth hole to use as one of the deep hole terminals for the communication experiment. We suggest, therefore, that during the fourth year seismic and electrical field surveys be conducted to find a path for an experimental link starting at the existing hole. If the waveguide connection exists, a desirable path for the experiment would be between the two sites surveyed during the second phase of the project.

If it is decided that the prototype experiments will be performed, this final phase of the program before drilling the deep holes would cost about \$900K. Most of this cost would be for field surveys extending the site surveys in Phase 2 in order to select the test range.

Total Phase 4 Cost                      \$900K

#### *Laboratory and Theoretical Studies*

In addition to the field surveys, it is critical that the proposed project include a continuous level of laboratory and theoretical studies supporting the interpretation of the field data. Each year the priorities in these supporting studies will emphasize the areas most directly applicable to interpretation of the field data for that year.

The laboratory studies will include 1) investigation of effects of microcracks, pores, and water content of rocks on electrical and seismic properties of the rocks, 2) investigation of conditions and rock types most likely to result in crack free zones, 3) investigation of the effect of temperature and pressure

levels expected in the crust on electrical properties of rocks, and 4) investigation of the general relationships between the electrical and seismic properties of the types of rock that can be expected in the deep crust. These studies and their objectives are discussed in more detail in Reference 3, Section IV.

The major goals of the theoretical studies will be to design an appropriate antenna for use in the deep holes and to estimate the sensitivity of the propagation to lateral resistivity variations and to variations in the vertical boundaries of the high resistivity zone.

The cost of these studies has been included in the estimated annual costs given above.

#### C. Costs by Fiscal Year

Assuming that the program outlined above begins in time for site selection surveys to be completed during the summer of calendar year 1972, the four phase program will take about 3-1/2 to 4 years. The four phases of the program, however, do not map directly into four fiscal years. An attempt is made below to assign costs to the appropriate fiscal period.

##### *Fiscal 1973*

The entire Phase 1 of the program will be funded and completed during this fiscal year. In addition, since the duration of Phase 2 approximately matches calendar 1973, at least half of the Phase 2 funds will have to be committed in fiscal 1973. Since field equipment and crews are normally scheduled for the complete field season before the season starts, it will be desirable and possibly necessary to commit the funds for the entire Phase 2 field effort in fiscal 1973.



Total funds that must be committed during fiscal 1973 will thus be on the order of \$2.7M to \$3.4M.

*Fiscal 1974*

During fiscal 1974, Phase 2 of the program will be completed. We expect Phase 3 to require about 1-1/2 years. The field work will be divided about equally between calendar years 1974 and 1975 when the drilling will be completed. The Phase 3 costs in fiscal 1974 will, therefore, include about 1/2 of the field work and 1/3 of the other Phase 3 costs.

Total funds that must be committed in fiscal 1974 will be about \$3,640K to \$4,340K.

*Fiscal 1975*

Fiscal year 1975 and the rest of Phase 3 of the program are approximately coincident so that 1975 fund commitment will be \$3,450K to \$4,150K.

*Fiscal 1976*

The final phase of the program discussed here will be completed in the first half of fiscal 1976 so the required fiscal 1976 funds will be just under \$1M. If it is decided to begin work on a prototype system, funds for initiating the drilling would also come out of this fiscal year.

D. Alternate Programs

*Accelerated Program*

The objectives of the proposed four year program could probably be completed in three years. The proposed program makes

optimum use of university field teams and existing or already planned equipment. Total cost of an accelerated three year program would be higher than the proposed four year program for two reasons: 1) procurement of additional equipment and, possibly, use of commercial crews would be required to perform sequential parts of the proposed program in parallel (particularly during the second year) and 2) procurement of ship time for parts of the oceanic survey that might have been done using ships of opportunity. The accelerated program would also require committing funds for some parts of the project which had not yet been justified by positive results from earlier experiments.

Since there will be very little time to organize the first year program, the only changes in the first phase would be to begin procurement of equipment and ship time for use during the second phase. This would add about \$500K to the funds committed for the first phase.

In the accelerated program, the major changes occur during the second phase when geological and geophysical field surveys of areas characteristic of different geologic conditions (including the suboceanic crust) would be carried out in parallel with the detailed studies of the two primary test sites. Although these additional surveys would include some electrical measurements, the surface conditions would probably not permit accurate electrical surveys of the deep crust, and the major increase in cost would be for seismic crews and equipment and for additional ship time. In this accelerated program the costs would probably peak during the second phase with expenditures of about \$10M including use of commercial seismic crews in some areas.

If the results of the second phase of the accelerated survey indicate that a high resistivity zone exists under a significant part of the earth, the intermediate depth test hole should be started as quickly as possible with the objective of completing and surveying the hole during the third year of the project. Surveys to select a potential test range terminating at the existing hole should also be conducted during the third year. The cost of the final phase of the accelerated program would be about \$5M.

The cost of the total accelerated program would thus be at least \$5M above the proposed program and much of the money would have to be committed before the benchmarks for the justifying experiments were reached.

#### *Decelerated Program*

Although slowing the program down would not save any significant funds over the total project, it would allow a lower annual expenditure at the expense of a longer program. If the project were discontinued at one of the crucial milestones because the experiments proved the high resistivity zone does not exist, the total funds committed prior to that decision may be less under the slower program. The decelerated program is easiest to describe by field year (approximately a calendar year).

Again, there is little change that can be made in the first year (equivalent to the first phase of the basic program) except possibly to examine fewer sites in the site selection survey. Since the selection of a good test site is crucial to the success of the whole program, this would be a false economy and we would not recommend it.

The cost of the second year program can be reduced to about \$2M by surveying only the better of the two selected sites. If the results of that survey are positive (it appears that a high resistivity zone exists), then it may not be necessary to survey the second selected site in such detail. If, however, the results of the first site survey are in doubt, the second site must be carefully surveyed during the third year at a cost of about \$1.5M.

If the results of either survey are encouraging, then the next crucial step would be to begin the intermediate depth hole. The oceanic part of the program could continue to be on a ship-of-opportunity basis for another year. During this (3rd or 4th) year, surveys of sites representing other geologic provinces should begin. Expenditures for this year would be about \$3.5M.

The next (4th or 5th) year would see the completion and survey of the hole and the start of the priority oceanic studies. The exploration of conditions in other geologic areas would be finished during this year. Total costs would probably be about \$3.5M for the year.

The final year (5th or 6th) would include completion of the oceanic survey and the selection and survey of an extension to the successful site to identify a potential test range. Expenditures for this year would be down to about \$1.5M.

#### IV. DISCUSSION

Two subjects relating to the experimental program and to the application of an electromagnetic communication link through the earth need to be discussed briefly in order to add some perspective to the suggested project.

It is clear from the proceedings of the workshops<sup>2,3</sup> and from AGU Monograph 14<sup>1</sup> that remarkably little quantitative information is available on the electrical properties of the deep crust and upper mantle. It is tempting to put off any expenditures on a major geophysical program for a couple of years in the hope that new relevant data may be generated in the normal course of geophysical research. Research on the electrical properties of the earth, however, generally emphasize measurements sensitive to low resistivity, near surface zones of interest to the mining industry. Although some deep crustal seismic measurements are being made, they are usually based on compressional wave energy that can be easily generated on land or at sea. On the other hand, shear wave propagation seems to be more sensitive than compressional wave to the properties of rocks that affect resistivity. Thus, without explicit, mission-motivated support for the type of program discussed here, very little relevant work will be done. We have reached a stage in our technology where we know what experiments must be done to obtain meaningful answers to the crustal resistivity question.

A useful communication system requires not only an appropriate medium for propagation of energy, but also a means of injecting energy into and collecting energy from that medium. If the necessary high resistivity zone exists in the earth, its upper boundary will be at least 5 kilometers and perhaps as much as 15



kilometers below the surface of a continent. A land based terminal (either transmitting or receiving) will require an antenna operating in a deep hole drilled at a cost likely to exceed \$10M. Either the coupling between the antenna and the medium must overcome the affects of a possibly very low resistivity region including the hole (possibly water filled) and the fractured zone resulting from the drilling of the hole, or new drilling procedures must be developed to insure that water is not injected into the fracture zone created by the drilling. For example, special drilling fluids may be required. The cost of such a hardened communication link between two land-based stations will certainly exceed \$20M and may reach as high as \$50M or more.

Beneath the ocean, the high resistivity zone will probably be within 4 to 5 km of the sea floor, but here the energy, if it is to reach the sea floor, must penetrate saturated subsea sediments which form a thin conductive layer. Whether an antenna can be placed directly on the sea floor, or would have to be jettied or drilled into the bottom, will determine the flexibility of using a suboceanic waveguide.

Possible geological complications to practical electromagnetic communication through the earth may be caused by temperature effects at ocean ridge systems and possibly by the geometry of island arc subduction zones which may produce barriers to an otherwise continuous waveguide. Thus there may be limitations on the possible paths over which such a system can be used\*.

\*ONR Code 417 has prepared a more detailed discussion of the possible applications of lithospheric communication to supplement this report.

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